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DAM OF THE ANADYRSK THERMAL ELECTRIC POWER STATION (PLOTINA ANA--ETC(U)
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DAM OF THE ANADYRSK THERMAL ELECTRIC POWER STATION

A.L. Kuznetsov

CORPS OF ENGINEERS, U.S. ARMY
COLD REGIONS RESEARCH AND ENGINEERING LABORATORY
HANOVER, NEW HAMPSHIRE

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THE DAM OF THE ANADYRSK THERMAL ELECTRIC POWER STATION

A. L. Kuznetsov

In 1964, a dam was constructed to supply water to the city of Anadyr' on the Chukotka Peninsula. The dam is 8.5 m high and 410 m long, and impounds a reservoir with a volume of about 1 million m^3. It is planned to increase the reservoir capacity nearly seven fold to meet the increasing requirements of the city and of the thermal electric power station under construction. This will require a dam 16 meters high (24 meters, including the toe), and a crest 1500 m long. The existing dam will be incorporated as the upper wedge of the new dam. The dam will be constructed in a permafrost area with severe climate and harsh engineering and geological conditions. This will be one of the largest dams built on friable permafrost sediment which settles after the soil thaws.

The installation will include a dam, self-regulating spillway, and a stilling basin with pump.

Climatic Conditions

The climate in the construction area is maritime, with continental features during winter. The average annual air temperature is -7.4° and the absolute minimum (January) is -47°. The absolute maximum (occurring in July and August) is +27°.

The average monthly air temperature during the winter months (October-May) varies from -3 to -22°. Summers are short and cool. The average monthly air temperature rises above 0° during only four months of the year (June to September). The relative humidity averages 84% for the year, (90% in some years). Each year 427 mm of precipitation fall, of which 160 mm occur in summer. Freezing rain often falls (9 to 13 days a month), lasting 8-10 hours a day. Evaporation from land and water during periods of positive temperature amounts to 254 and 137 mm annually, respectively.

The snow cover lasts about 230 days a year on the average from mid-October until late May or early June. However, snow may fall at any time throughout the year.

The snow-cover distribution is extremely irregular. The average thickness in areas exposed to the wind is 50-80 cm. Drifting snow accumulates in depressions, on houses,

and on other structures, reaching 2-5 m in thickness, and with a density of 0.5 to 0.7 g/cm^3. Thaws lasting 1 to 3 days can occur in any winter month.

The wind conditions are of a "monsoon" nature. During the warm season, southeasterly (and less often, easterly) winds predominate, blowing from the Bering Sea. In winter, winds from the dry land to the northwest and west prevail. Maximum wind velocity in summer reaches 30 m/s, in winter 50 m/s. At wind velocities above 15 m/s and with negative temperatures, it is impossible to work outdoors.

Other unfavorable climatic features are blizzards, ice storms, freezing rain, and fog.

Blizzards begin in September and end in May. There are an average of 73 days a year with blizzards. Blizzards are most frequent in March, and occur on as many as 25 days in some years. Sometimes they occur in June and August. No blizzards have been observed in July, although snowfall is possible.

July and August are the only months without freezing rain, and it does not occur every year in the remaining months. Freezing rain is deposited on wires, whose weight can reach 136 g/meter.

Freezing fog is observed during 9 months (except July, August, and September). There are an average of 38 days a year with freezing fog; some years it lasts for 10-15 days on end. The weight of frozen-fog deposits on wires can reach 1083 g/meter. Freezing fog and freezing rain threaten power transmission wires, which may break under the weight and strong wind. These phenomena complicate road traffic considerably as well.

Fogs are most frequent in spring and summer (14-16 days a month), and are less frequent in autumn (9-10 days a month).

Engineering, Geological, and Permafrost Conditions

The valley of the Kazachki River has two terraces in the vicinity of the construction site. The first is 3 m above the bottom of the river, and the second, which is not clearly evident everywhere, is 2-5 m above the first,

sloping toward the river. The river bed is 5-10 m wide. The natural surface is tundra, devoid of vegetation and covered by peat, with a characteristic polygonal micro-relief in many areas, indicating the presence of repeated splitting by ice formation (Figures 1-2). In many parts of the tundra, thermal karst has developed: ditches, small pools of water, dry lakes and "allasy." For about 800 m, the section line of the dam will run along the natural surface of the tundra, and about 500 m behind the existing dam, at 45 m from its axis, with discontinuous natural relief. The thermal karst features are maximally developed in this area [pits, ruts, considerable thawing (2 meters down), temperature of frozen soil higher than that of the tundra].

In the foundation of the future dam, beneath a layer of peat 0.5 to 2 m thick, there is a loose layer of deluvial, solifluction, and alluvial deposits up to 8 m thick, composed of sandy loam (layers 3 and 4), loamy clay (layer 2), and sand and gravel (layers 5, 6, 8) (Figure 3).

These deposits are permanently frozen, with the exception of the talik in the bed of the Kazachki River and a layer of soil which thaws seasonally. The soils are characterized by high ice content (20-60%), with a specific gravity of 1.4 to 1.95 tons/m^3 and a skeleton weight of 0.74 to 1.5 tons/m^3. A system of polygonal ice crystals has formed in these deposits. The average distance between these veins is 10-12 m. The veins are up to 7 m thick (from the base of seasonal thawing). The width of the wedges at the top varies from 0.5 to 4 m. In many cases, the upper parts of adjacent veins are combined, forming a continous ice cover.

The soil settles as it thaws. The degree of settling resulting from thawing of the structural ice is determined by the thawing factor $A = 0.15$ to 0.5 and the consolidation factor $a_0 = 0.01$ to 0.04.

When the soil thaws completely, settling averages 2.5 to 3 m and no more than 1 m in the river-bed section of the dam.

The deluvial, solifluction, and alluvial deposits rest upon marine clays and argillaceous soil, which settle only slightly after thawing ($a_0 = 0.05$) and are practically non-filtering ($K_f = 0.005$ m/day).

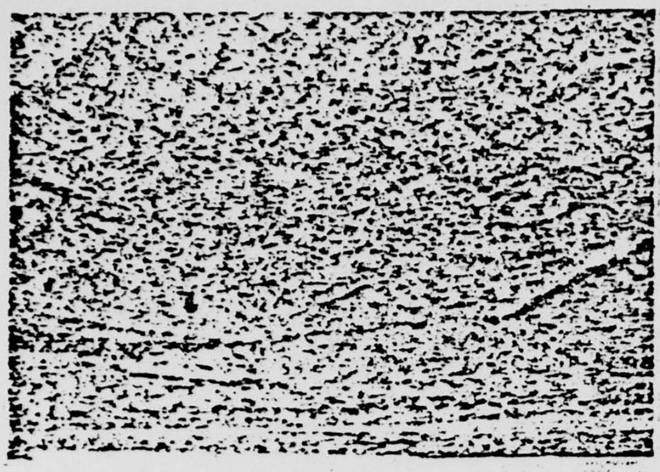

Figure 1. Polygonal Microrelief of the Dam Construction Site. The collapsed grooves are traces of thawing of the ice veins shown in Figure 2.

Figure 2. Cross Section Along an Ice Vein. The ice is covered with layers of grass and peat.

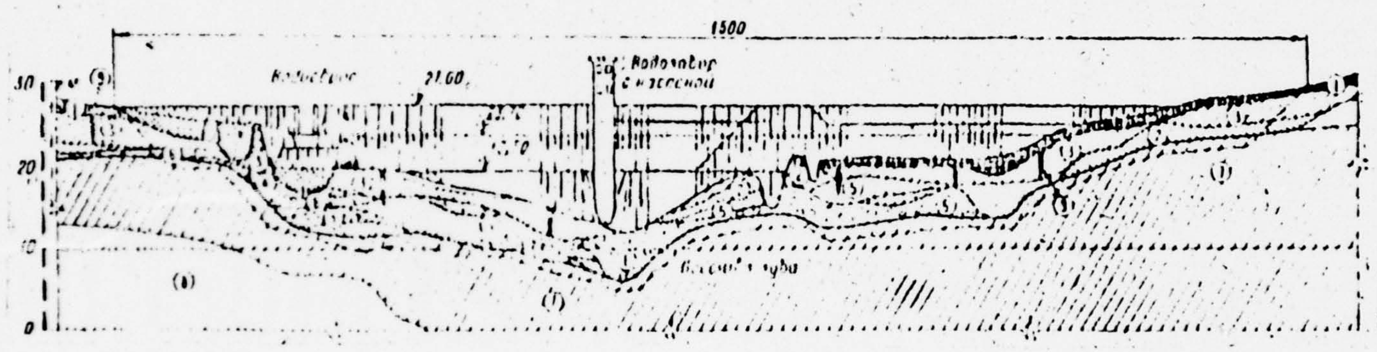

Figure 3. [Caption illegible]

Temperature Regime of Foundation Soils

The dam will be built in a permafrost area where the permafrost is 100 to 150 m thick. The permafrost is thicker in the elevated parts of the relief (hills and mountains), and shallower in the river valleys. The soil in the foundation of the planned dam is permanently frozen, with the exception of the Kazachki River bed, up to 10 m wide, and the existing spillway, about 20 m wide, where there are shallow taliks up to 4-6 m deep, as well as a seasonally thawing layer 0.3-2 m thick, which freezes in winter and merges with the permanently frozen soil. The temperature regime of the permafrost is inhomogeneous. The characteristics of such soils naturally depend largely upon their temperature.

As far as the temperature regime of the foundation soils is concerned, areas can be picked out which are distinguished by the thickness of the layer of annual temperature variation, the temperature of the soils in the cushion of this layer, the nature of the annual temperature fluctuations, the depth of seasonal thawing, and the average annual surface temperaure. These differences are determined by the geomorphological locations of the areas, their different snow covers, exposure to solar radiation, the degree of disruption of the relief, and the nature of the surface vegetation.

The left-bank and central parts of the dam foundation are areas with a broken relief (area of the existing structures on the Kazachki River). The depth to which variations in the annual temperature occur is about 5 m; the soil temperature at the level of year-round negative readings is -1.5°, and the average annual soil temperature at the natural surface is -5°. The depth of seasonal thawing is 2 to 3 m (September-November).

The right-bank section of the dam foundation is a natural surface of undisturbed tundra. The depth subject to variation in annual temperature is 10 to 12 m; the temperature at the level of year-round negative reading is -4.8°; the average annual temperature at the surface is -5.5°; and the depth of seasonal thawing is 0.4 m.

The talik in the bed of the Kazachki River is about 6 m deep and 10 m wide. The temperature in the talik is 2 to 8°. The talik begins to freeze in late September, starting at the bottom, and by the end of October the zero isotherm has risen 3 meters. The freezing process begins from the top at the end of October. After 5 to 10 days the

talik has frozen down from the top to a depth of 0.4 to 0.5 m; it then remains unchanged for two months, until early January. This is due to the warmth produced by snowdrifts. By the end of the winter the snow cover is 4 to 5 meters thick. The thickness of the talik in the river bed is about 2 m, and the temperature of the talik is about +2.5°. At the end of June, after the snow has melted, the talik grows back to its original dimensions. Its depth is 3.5 to 4 m in the existing spillway channel. The minimum temperature (on the basis of observations) of the talik in September is +9.5°, and at the end of December, it is +2.6°. In winter the channel is filled with snow to a depth of 4 to 5 m. The lack of an annual observation cycle has prevented us from drawing any conclusions about the talik during winter.

Hence, a characteristic feature of the temperature regime of the soil near the existing structures is the higher temperature of the frozen soil in the foundation by comparison with the temperature of the soil in the undisturbed tundra surface. This is due to the warming effect of the snow. In summer the heat penetrates to a considerable depth, thanks to the disruption of the soil or lack of natural grass and peat cover, while the soil is prevented by the snow cover from cooling in winter. The snow cover reaches 3 to 5 m in the lower pool of the dam.

Temperature Regime of the Existing Dam

The existing dam is frozen. The soil temperature at a depth of 10 to 12 m varies from -2.8° in the left-bank foundation to -1° near the river bed. This characteristic of the temperature regime is explained by the preferential penetration of the seasonal heat, while the soil is prevented from cooling in winter by the snow cover, 2.5 to 4 m thick.

Toward the end of the warm period (August, September) the dam thaws from the crest and toe to a depth of 1.5 to 2 meters. In late October, the part which has thawed begins to freeze again. In the river-bed part, filtration occurs in the foundation, gradually decreasing from October to December and then remaining constant throughout the winter, to increase again in June.

Seasonal filtration through the body of the dam is observed in the section of the dam which is 30 to 40 m thick and located near the river bed. Discharge of filtration water at the toe of the dam occurs when the soil-thawing

limit in the dam has fallen 20 to 30 cm below the water level in the reservoir. As negative temperatures develop after the soil freezes, filtration ceases. An examination of the dam in August 1968 (four years after the project was started) showed that along its crest, near the top of the lower and upper slopes, there were many cracks up to 50 m long and 2 to 3 cm wide. Crack formation was associated with deformation of the foundation beneath the upper and lower wedges as a result of (1) the thermal action of the reservoir and (2) the thermal karst.

<u>The Planned Dam</u>

A cross section of the dam is shown in Figure 4. In its central part, there is a core, provided with a toe in a clay foundation (layer 11). The depth of the toe can be up to 8 meters. The core and toe are formed from rottenstone-rubble loam with a melkozem content (smaller than 2 mm) of 50 to 95%, with an average of 68%. The specific gravity of the soil skeleton is 1.6-1.8 tons/m^3, optimum moisture is 15 and 22% for loam, while the filtration factor is 0.01 to 0.001 m/day.

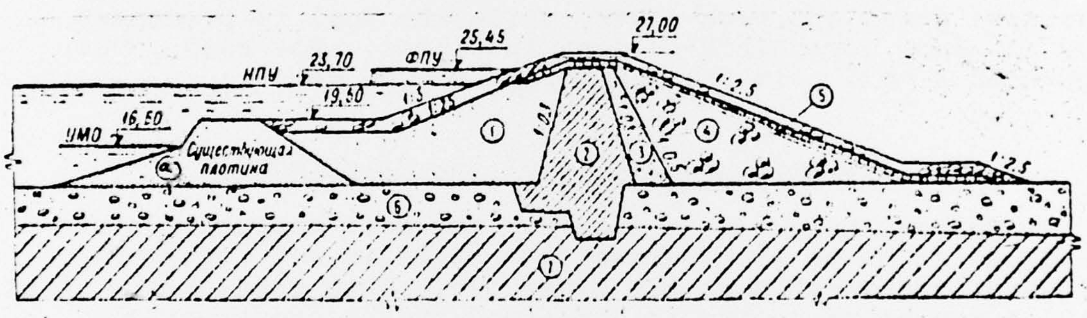

Figure 4. Cross Section of Dam
1, sand and gravel and rottenstone-rubble soil;
2, rottenstone-rubble soil;
3, intermediate layer - rottenstone-rubble soil;
4, riprap;
5, soft soil, peat, rock;
6, same as Figure 3;
a, existing dam.

The upper wedge of the dam is formed from soft quarry sandy loam and rottenstone-rubble soil of different compositions. To protect against wave action, unsorted rock (riprap) was placed along the upper edge. Within the limits of the foundation of the upper wedge, peat was excavated as well as a meter-thick layer of soil which contained mostly ice (up to 80%). For a distance of 410 m, the existing dam will be incorporated in the upper wedge of the planned dam.

The lower wedge of the dam will be formed fomm riprap (rock material) on a natural frozen foundation without excavating the peat. Between the core and the riprap there will be an intermediate layer made of natural rottenstone and rubble, with a loose-stone content of about 60% (larger than 2 mm). Making the lower wedge of riprap will shorten the freezing time for the clay core of the dam during construction.

In order to prevent thawing and to maintain negative temperatures in the lower wedge in summer, the toe of the dam will be covered by a heat-insulating layer made of soft soil 0.5 m thick and by 0.6 m of peat, protected against atmospheric effects by a layer of rock.

Hence, the lower wedge will be a "cold sink" which will maintain negative temperatures in the core.

To reduce the depth of seasonal thawing and to protect the core against the formation of frost-produced cracks, the crest and a portion of the upper spillway will also be covered with a layer of peat until water begins flowing.

Basic construction work on the dam (excavation of 180,000 m^3 of frozen soil, fill amounting to 645,000 m^3, including 475,000 m^3 of wet soil, and 170,000 m^3 of loose soil) is expected to be complete in three and a half years.

The foundation will be prepared in autumn and winter. The soil in the toe of the dam is scheduled to be added during negative temperatures in spring (April and May) and autumn (October and November).

Work during December and March will be difficult, and in some areas impossible, due to the strong winds and heavy snowfall.

The dam will be compacted by rollers and compacting machinery.

Considerable difficulties are bound to arise in solving problems associated with the development and preparation of frozen icy soils in the open-pit area under the conditions of a short, cool summer. The total soil moisture of the various layers will be 23 to 59%, with a maximum of 115%. This soil must not only be worked, but must also be given the optimum moisture content: in the case of rottenstone-rubble soil, 15%; clay, 22%. Figure 5 shows the loose soil after it thaws in the test area.

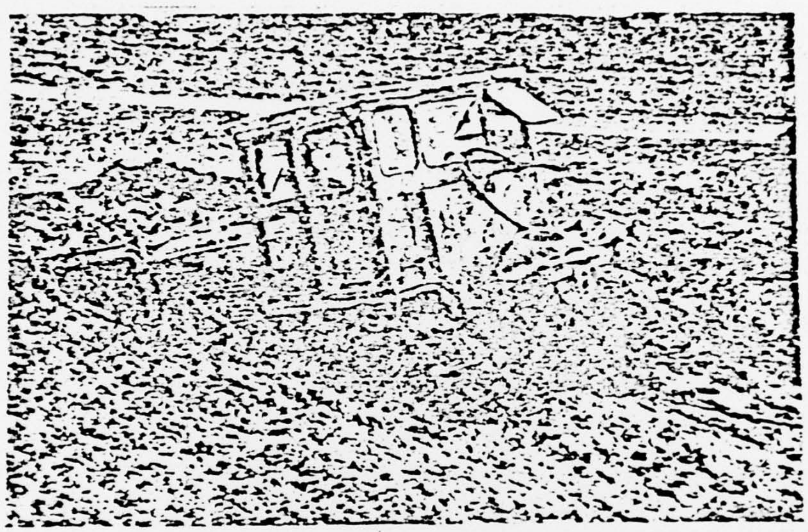

Figure 5. Preparing Thawed Soil (Clay, Loam) in the Test Area. Total moisture content = 60%.

The soils in the open-pit area, as they thaw naturally (3 to 7 cm/day), will be worked with bulldozers with mixing rollers; after they are partially loosened, they will be shifted repeatedly by a bulldozer to reduce their moisture. Then the soil will be loaded into dump trucks and transferred to "burty"* up to 12 m high, where it will dry out further. Seventy-five percent of the soil will be stored

* "Burty" = collar-like structures to store potatoes, etc. in fields. Translator's note.

in this way, and 25% will de dumped directly into the dam from the pit.

Temperature Regime of the Dam

Construction and operation of dams in permafrost soils which settle after thawing has certain specific characteristics. The reservoir formed by the dam will act as a constant heat source, influencing changes in the temperature regime of the body of the reservoir, along its edges, at the bottom of the upper wedge, and in the body of the dam.

As a result of thawing, the physical and mechanical properties of the permafrost soils will change, and their supporting ability will decrease.

In nonfiltering dams, the foundation thaws only along the upper wedge; in filtering dams, however, it occurs over the entire foundation. As the icy foundation thaws, it settles, causing the body of the dam to sag, and filtration to increase, resulting in loss of soil (erosion), which can destroy the dam.

Experience in the construction and operation of dams under permafrost conditions indicates that dams built on soils which settle after they thaw can be operated successfully only if they are of the nonfiltering type, and are frozen. Therefore, it is very important to determine the temperature regime of the dam as a whole, as well as in the locations in contact with other structures and with the foundation.

Dams can be kept frozen by natural freezing during construction and during the first few years of operation, or by artificially freezing the body of the dam, using cold winter air or liquid coolants. These soil-freezing methods were discussed in the planning stage.

Artificial freezing of soil using coolants (calcium chloride, sodium chloride) is widely used to strengthen soil and to reduce filtration when building temporary dikes. This method is not used for permanent structures because prolonged operation of the system leads to intensive corrosion of the pipes and leakage of coolant into the ground. Leakage of coolant is also possible if the pipes are poorly installed. Soil was contamined by salt in a dam on the Dolga River, so that the use of air and coolants to freeze

the soil in the core of the dam was replaced by the air method.

Freezing soils by using cold winter air has been used successfully for dams on the Dolga River, as well as the Myaundzhe and Irelyakh Rivers. Experience in operating the freezing systems in these dams has shown that the freezing pipes are efficient at ambient air temperatures no higher than -15°; as they operate, the air is heated 3 to 5° by the fan, and also along the length of the pipe, reaching 50% of the temperature of the incoming air. The average winter air temperature in the construction area is -14.8°. This is inadequate for efficient freezing of soil. The number of days on which the air temperature is -15° is less than 130. Nearly the entire winter period was required to construct the underground wall. Therefore, an air-type freezing system must be installed and turned on in early winter.

In view of the complexity of the engineering and geological conditions, and the presence ofpolygonal veins of ice, intersecting the axis of the dam, the toe of the dam must be built by cutting through the friable deposits of wedge-shaped ice, even when permafrost is present.

Using the permafrost curtain will cause considerable difficulties associated with the features of the climate. Frequent thaws, which can occur during any month in winter, will require the permafrost curtain to be shut off. A violent snowstorm may blow snow down into the shafts, especially during periods when they are not working. The temperature and humidity conditions may change in the freezing pipe. Dew may collect and form icicles and ice plugs in the spaces in the pipes between the tubes. The latter occurred in the freezing pipes on the Irelyakh River, even under the most favorable climatic conditions.

For the reasons given above, under the conditions existing on the Anadyr River, operation of an air-freezing system will not be sufficiently efficient, especially during the first year, and will cause difficulties during operation.

Temperature Conditions in the Dam, Taking the Natural Freezing Process into Account

To determine the temperature regime of a dam with natural freezing of the soil, heat-engineering calculations

were made.* The presence of a talik in the river bed and of permafrost soils in the flooded area made it necessary to perform calculations for two cross sections of the dam, in the river bed and in the flooded area.

In view of the low filtration factors of the soils in the core (K_f = 0.01 to 0.001 m/day) and of the loam in the foundation (K_f = 0.005 m/day), the computations for the flooded area and the bed were the same as for a "non-filtering dam." In the case of the river bed containing the talik, a calculation was performed which took into account the filtration of the soils in the body and foundation of the dam (a "filtering dam").

Non-Filtering Dam

Figure 6 shows the results of the calculations for the dam during flooding.

Original Conditions

1. The temperature of the soil poured into the dam was assumed to be +5°.

2. It was assumed that the dam was created "instantaneously" on the first of October.

Boundary Conditions

1. The soil freezes during the winter, with an average winter temperature of

2. In May, the dam accepts its head. The average summer temperature of the water in the reservoir is 6° (May-October).

3. Beginning on October 1 of the first year of operation, calculations were made on the basis of average annual data; the water temperature in the reservoir is +3.3°. The air temperature is -7.4°.

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* The calculations were performed by the Gor'kiy Engineering and Construction Institute (GISI) using the method of P. A. Bogoslovskiy, and by the Siberian branch of VNIIG, using its own method.

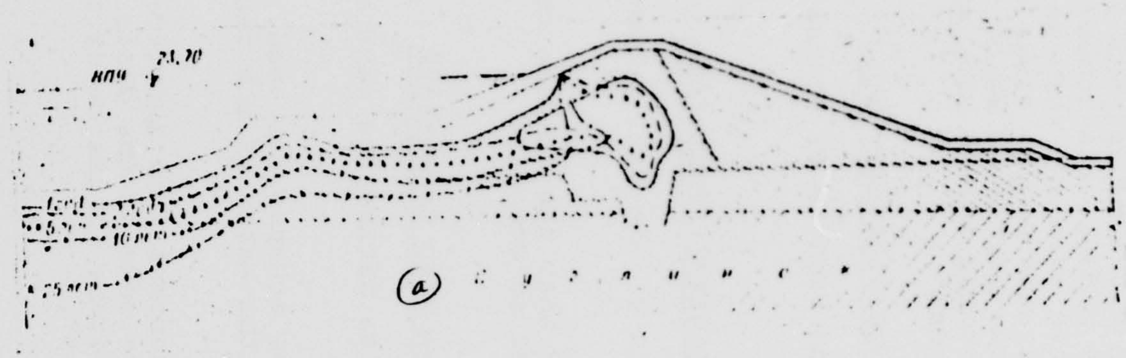

Figure 6. Results of Heat-Engineering Calculation of the Dam. Position of zero isotherm in the first, second, fifth, tenth, and 25th years of operation. a, clay.

Filtering Dam

Calculations of the filtering dam with a talik in the foundation showed that even when we take into account the filtration of the soil in the dam (K_f = 0.001 m/day) and the foundation (K_f = 5 m/day), the soil in the dam is frozen by natural processes.

Results of the Calculations

A dam which is raised to its final height in one season (assumed to be an instantaneous process in the calculation) freezes along the edges during winter. Along the upper pool, freezing is 4 to 4.5 m deep. The riprap freezes to a greater depth. By the end of the summer of the first year of operation, the upper spillway has thawed to a depth of 3.0 to 3.3 m. Thus, the upper spillway contains a frozen layer (apron) more than 1 m thick, while the central part of the dam contains a thawed zone. The presence of the frozen apron on the upper pool side rules out any filtration through the dam.

In subsequent years, the frozen layer thaws but the size of the thawed zone decreases (the soil freezes through). By the end of the tenth year, the core has completely frozen through.

The entire dam actually will take three years to build. The individual sections must be built in one or two summer seasons, and freezing will require 1-3 winter periods, in other words, when the freezing conditions will be more favorable. Preliminary calculations based on the actual time required to build the dam show that the central part will freeze by the third or fourth year of operation, while the toe will freeze when the reservoir begins to fill.

Calculations of the temperature regime in the dam, taking into account its stratified structure during the construction period, will be performed at the working-drawing stage. Calculations on an engineering model have shown that during the operation of the dam, there will be two temperature zones: a frozen one (the central part and lower wedge of the dam) and a thawed one (upper wedge and to some degree, the foundation beneath it).

Deformations of the Dam

Deformation of the dam was examined on the basis of heat-engineering calculations.

The ice foundation beneath the upper wedge of the dam begins to melt five years after the soil in the upper wedge has thawed; the latter freezes through during construction.

Ten years later, the soil has thawed to a depth of 2.5 to 3 m and after 15 years reaches 5 m; the sediment has only reached 1 to 1.5 m.

Total thawing of the settled soil in the foundation extends about 8 m and occurs during the 25th year of operation, while settling reaches 3 m.

In order to rule out deformations of the upper wedge, it would be necessary to replace the soil which settles after thawing by soil that does not settle, with a volume of about 300,000 m^3. The cost of this measure would be several millions of rubles.

The rate at which the soil in the foundation thaws beneath the upper wedge of the dam over 10-15 years will be about 0.5 m a year on the average, and will then decrease to 0.4 to 0.2 m per year.

In view of the fact that the filtration factor of the thawing soil is 0.1 m/day or more, consolidation will take place quite rapidly.

Since the soil will thaw gradually, deformation will not pose a danger to the dam. Therefore, it was decided to use a solution which would not involve excavation of soil in the foundation of the upper wedge of the dam.

Settling of the upper wedge and the foundation beneath it do not influence the settling of the central and lower parts of the dam, which are frozen.

CONCLUSIONS

1. When building dams in permafrost regions, positive experience in construction and operation of dams under these conditions cannot be transferred automatically. The climatic and permafrost-geological features of the construction site must be taken into account.

2. During the construction and operation of a dam, the temperature regime of the soil in the foundation will change, not only on the upper pool side but on the lower pool side as well (thermal karst phenomena, settling of the lower pool, etc.), and must be taken into account in planning.

3. Both artificial and natural freezing of the body of the dam must be considered, if avoiding freezing systems will result in considerable savings and if the climatic and engineering-geological conditions at the construction site allow.

4. The soil in the foundation thaws more slowly, the thawed ground gradually consolidates itself, and there is no pronounced settling of the soil in the foundation or the upper part of the spillway in both cases. There, no excavation is needed to remove the settled soil from beneath the upper wedge.

5. To speed up the freezing of the central part of the dam (especially during the construction period) it is advantageous to make the lower wedge of the dam of porous soil which freezes rapidly (sand and gravel, rubble and riprap).

6. To protect the lower wedge against thawing and to maintain stable negative temperatures in it during the summer, the lower slope of the dam must be protected by thermal insulating coverings.

7. In the upper wedge of the dam, it is necessary to use soft soil, which is a heat insulator and reduces the heat flux from the reservoir.

Dumping loose soil into the upper wedge makes the temperature regime of the dam worse: the zero isotherm in this case will be displaced toward the lower slope and the core will be thawed; this cannot be allowed when soil which may settle is used in the foundation.